

## INVITED PAPER

### Highlights on the interaction between SNRs and the surrounding medium

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**Abstract.** When a star explodes as a supernova (SN), about  $10^{51}$  ergs of energy are released in the interstellar medium (ISM). Most SN outbursts occur near or inside the molecular clouds where their progenitor stars were born. An increasing number of SN remnants (SNRs) show signatures of being interacting with neighbouring clouds. Understanding such interactions is crucial both to determine the physical and dynamical conditions and structure of the ISM and to learn about the physical processes that take place in an SNR shock front. Even if molecular clouds are absent, pre-existing magnetic fields can play a key role on the morphology of an SNR. In this paper I review some recent results on the interplay between Galactic SNRs and their surroundings.

**Resumen.** Cuando una estrella explota como supernova (SN), se liberan unos  $10^{51}$  ergios de energía en el medio interestelar (MIE). La mayoría de las explosiones ocurren cerca o dentro de la nube molecular donde nacieron las estrellas progenitoras. Cada vez más remanentes de supernovas (RSNs) muestran evidencia de interacción con nubes vecinas. Comprender tales interacciones es crucial tanto para determinar las condiciones físicas y dinámicas y la estructura del MIE como para conocer los procesos físicos que se dan en el frente de choque de un RSN. Aún en ausencia de nubes moleculares, los campos magnéticos pre-existentes pueden ser determinantes en la morfología de un RSN. Este artículo presenta una recopilación de los resultados más recientes sobre la influencia mutua entre RSNs galácticos y sus entornos.

## 1. Introduction

The study of interactions between supernova remnants (SNRs) and the surrounding medium can give us insight on several aspects related both to the interstellar medium and to the SNR itself. The analysis of the H I associated to a SNR gives information on the swept mass and explosion energy and sets limits to the distance. Molecular shocks are useful to study the chemical reactions that take place in unique conditions, impossible to reproduce on Earth-based laboratories. The detection of OH masers at 1720 MHz strongly constrains the physical properties of the shock front and, by Zeeman effect, makes it possible to measure the magnetic field of the shocked gas.

Approximately 85% of Galactic SNRs are estimated to be produced by core collapse SNe, implying that their progenitors were massive stars. Since such stars undergo

a rapid evolution, by the end of their lives they are expected to be close or inside their parental clouds (e.g. Huang & Thaddeus 1986). Therefore, there is a high probability that most SNRs are interacting with molecular clouds. Moreover, SN explosions are likely to take place in an environment locally modified by the strong winds of massive stars during their lifetimes, which can create bubbles, tunnels or bow shocks.

Indicators of SNR-molecular cloud interactions include spectral line broadening, anomalous ratios between lines at different excitation levels, presence of shock tracer molecules like  $\text{H}_2$ ,  $\text{HCO}^+$ ,  $\text{SiO}$  or  $\text{SO}$ , or detection of OH masers at 1720 MHz. There is growing evidence of the influence that shocked molecular gas has on cosmic rays (CR) acceleration, as suggested by recent high energy observations. This issue will be discussed in the following section.

## 2. Gamma-ray observations

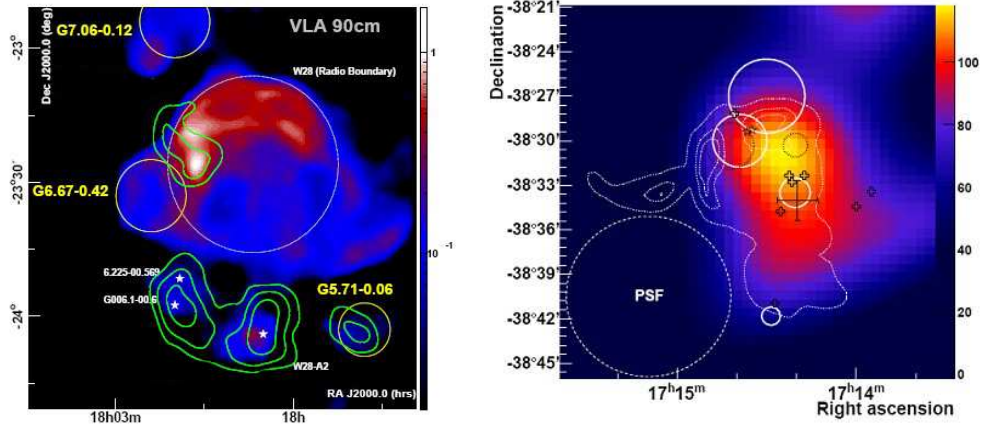
Galactic CRs are believed to be accelerated in SNR shock fronts; however, since they do not radiate efficiently, such hypothesis is hard to be tested. An approach to find evidence of CR acceleration is the detection of  $\gamma$ -ray emission from SNRs interacting with molecular clouds. Such systems are potential high-energy emitters by neutral pion-decay in hadronic interactions, where molecules would be the targets for accelerated CRs escaping from SNR shock fronts.

An example can be found in W28, an evolved SNR about one-degree in size, which is interacting with a molecular cloud to the west (e.g. Frail, Goss & Slysh 1994). Aharonian et al. (2008a) reported the detection of two TeV sources towards this SNR with H.E.S.S. (Fig. 1(a)). One of them lies to the west, in projection onto the molecular cloud as detected with NANTEN (see also Giuliani et al. 2010). The other source lies to the south of W28 and appears to be related with star formation in the field H II regions. The agreement between the former H.E.S.S. source and the Western molecular cloud strongly suggests that the  $\gamma$ -ray emission is of hadronic origin. Aharonian et al. (2008a) estimate that in such case, the CR density should be  $\sim 10$  to 30 times higher than the local value, pointing to W28 as the CR supplier.

W28 was recently detected in GeV with the Fermi Large Area Telescope (Abdo et al. 2010) and in MeV and GeV with AGILE (Giuliani et al. 2010). Combining data from AGILE and H.E.S.S., that is, in the MeV-TeV energy range, Giuliani et al. (2010) conclude that a hadronic scenario is the best explanation for the origin of the  $\gamma$ -rays. Abdo et al. (2010) included radio continuum data and considered three models to fit the energy spectrum, where the dominant mechanism of emission for each model was alternatively (a) Inverse Compton (IC) scattering, (b) electron bremsstrahlung, or (c)  $\pi^0$ -decay. Cases (a) and (b) need a low gas density which is incompatible with the presence of a molecular cloud. Therefore, a hadronic origin appears as the most likely explanation for the high energy emission.

CTB 37A represents another case of a SNR interacting with a molecular cloud (Frail et al. 1996, Reynoso & Mangum 2000), with two sets of OH 1720 MHz masers at different velocities, one set around  $-65 \text{ km s}^{-1}$  associated with this SNR, and the other around  $-24 \text{ km s}^{-1}$ , with origin in the overlapping SNR G348.5-0.0, seen in projection to the East. A H.E.S.S. source has been detected towards the center of CTB 37A (fig 1(b)) in coincidence with extended X-ray thermal emission (Aharonian et al. 2008b). A hard ( $\gtrsim 10 \text{ keV}$ ) X-ray compact source compatible with a pulsar wind

nebula, was additionally detected with Suzaku projected on the West of the extended emission (Sezer et al. 2011).



(a) Radio continuum image of W28 with VHE emission detected with H.E.S.S. overlaid in green contours. SNRs present in the field are indicated with white circles.

(b) VHE emission detected with H.E.S.S. towards CTB 37A. Radio continuum contours are included. The black open crosses and stars are OH masers at 1720 MHz, while the white circles represent CO clouds.

Figure 1. H.E.S.S. sources associated with W28 and CTB 37A (images courtesy of the H.E.S.S. collaboration<sup>1</sup>).

Aharonian et al. (2008b) considered different models to describe the spectrum of CTB 37A. A leptonic origin for the very high energy (VHE;  $E > 100$  GeV) emission, either by IC or electron bremsstrahlung, is unlikely due to the absence of non-thermal synchrotron X-ray emission from the clouds; a hadronic dominated scenario is more likely. In such case, the conversion efficiency from mechanical energy to CR varies from 4% to 30% depending on the range of molecular densities adopted. However, if the assumption that the emission is produced inside the clouds is relaxed considering that the VHE resolution is comparable to the size of the clouds, an association between the VHE emission and the candidate PWN seems reasonable. Castro & Slane (2010) found that the spectrum obtained with  $\gamma$ -ray data from Fermi-LAT and H.E.S.S. is well fit with a power-law and therefore they do not rule out a pulsar origin. However, since no nearby ATNF pulsars have been detected, a hypothesis based on interaction with a molecular cloud seems more appropriate. Such model requires a cut-off energy of 80 GeV for the protons.

Castro & Slane (2010) also fit spectra to 3C 391 and G349.7+0.2, two SNRs detected with Fermi-LAT which are known to be interacting with molecular clouds. They both are well fit by a power law model in which the cutoff proton energy is 100 TeV and 160 GeV respectively. There is a noticeable difference between the densities obtained from fitting the  $\gamma$ -ray or the X-ray spectrum, which may indicate that the contribution to the  $\gamma$ -ray emission of clouds close to SNRs is dominant, and are produced by CRs escaping from the shock front.

<sup>1</sup><http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/>

### 3. $\gamma$ -ray sources and OH maser SNRs

All the SNRs discussed in the previous section are known to be interacting with molecular clouds because they have OH masers at 1720 MHz associated. These masers are collisionally excited and appear when a SNR shock front hits molecular material, provided that the shock is of C-type with velocity between 25 and 50 km s<sup>-1</sup>, the temperature varies between 80 and 200 K, and the gas density is  $10^3 \leq n_{H_2} \leq 10^5$  cm<sup>-3</sup> (Elitzur 1976). A number of surveys (Frail et al. 1996, Yusef-Zadeh et al. 1996, Green et al. 1997, Koralesky et al. 1998) revealed that 23 SNRs ( $\sim 10\%$  of the catalogued SNRs) have OH 1720 MHz masers associated. Measurements of the Zeeman effect in these masers (Brogan et al. 2000) made it possible to estimate the magnetic field for the shocked gas.

Hewitt, Yusef-Zadeh and Wardle (2009) have analyzed if there is a correlation between OH 1720 MHz masers and  $\gamma$ -ray emission associated with SNRs. Using statistical tests, they conclude that there is a strong correlation that can be explained by the slight OH density enhancement triggered by the CR diffusion (Wardle 1999). The X-ray and CR fluxes arising in the SNR shock front, can increase the ionization flux by an order of magnitude or more, creating energetic electrons that collide against the H<sub>2</sub> molecules. The H<sub>2</sub> thus excited, de-excite radiatively producing a weak UV flux enough to dissociate H<sub>2</sub>O molecules in the shock front, yielding the warm OH necessary for the 1720 MHz maser emission. The OH column density that produces such emission is in the order of  $10^{16} - 10^{17}$  cm<sup>-2</sup> (Wardle 1999, Pihlström et al. 2008).

The correlation study carried out by Hewitt et al. (2009) revealed that ten of the 24 known maser SNRs have GeV or TeV-energy associations. The authors found that CR densities are typically 30 to 150 times higher than observed in quiescent clouds, and that the CR ionization is comparable to, or sometimes dominant over, thermal X-rays ionization. The tight correlation between OH 1720 MHz masers and  $\gamma$ -rays in SNRs renders  $\gamma$ -ray sources a powerful tracer of SNR-molecular cloud interactions.

## 4. Maser emission in SNRs

### 4.1. Extended emission at 1720 MHz

While the presence of OH masers at 1720 MHz constitutes a conclusive proof of interaction between a SNR and molecular gas, their detection is rare. Less than 10% of the currently catalogued SNRs have OH 1720 MHz associated. For example, Reach et al. (2002) observed the H<sub>2</sub> 2.12  $\mu$ m line towards 3C 391 and found several pre-stellar clumps gravitationally bound. The clump coincident with the single OH maser detected in this SNR amounts only to 3% of the total H<sub>2</sub> luminosity. This means that OH 1720 MHz masers are not biunivocal tracers of molecular shocks.

In a search for OH masers near the Galactic Centre, Yusef-Zadeh et al. (1999) detected extended maser emission at 1720 MHz in two SNRs: G357.7+0.3 and Tornado. In a subsequent paper, Yusef-Zadeh, Wardle & Roberts (2003) also detected extended OH maser emission at 1720 MHz in W28. Recently, Hewitt (2009) carried out a systematic survey for extended emission in SNRs, with positive results for 10 out of 13 SNRs known to be associated with OH 1720 MHz masers. This suggests that extended maser emission in SNRs is quite common. In that case, maser emission from large, nearby SNRs should not be detectable in interferometric surveys with long baselines, such as those performed by Frail et al. (1996), Yusef-Zadeh et al. (1996), Green et

al. (1997), and Koralesky et al. (1998). In addition, Hewitt & Yusef-Zadeh (2009) surveyed 30 newly discovered SNRs (Brogan et al. 2006) and several other SNRs combining single dish Green Bank Telescope (GBT) and VLA observations in the D array, and detected OH masers in 4 SNRs at levels that would have been impossible to detect in the previous surveys. This means that the existing surveys are far from complete. In two SNRs, Kes 69 and IC 443, the regions of extended maser emission are not coincident with the velocity or location of the compact masers (Hewitt, Yusef-Zadeh & Wardle 2008).

Extended OH maser emission at 1720 MHz is an excellent tracer of molecular shocks. As an example, let us consider the case of W44, which is embedded in a molecular complex and is associated with OH masers (Claussen et al. 1997). Reach, Rho & Jarrett (2005) surveyed this SNR in different molecular lines and found clear signatures of interaction at the location of the OH masers. Moreover, the authors also found that the H<sub>2</sub> emission at 2.12  $\mu\text{m}$  is distributed in filaments that run parallel to the radio continuum ones. W44 is one of the 18 out of 95 surveyed SNRs with clearly associated emission in the infrared bands detected with the IRAC camera in the Spitzer Space Telescope (Reach et al. 2006). The emission is stronger in the band where molecular lines are dominant, implying that the radiation comes from molecular shocks. Hewitt, Yusef-Zadeh & Wardle (2009) observed W44 in all four OH ground state lines, and detected extended filaments in emission at 1720 MHz and in absorption at 1667 MHz to the NE, in good agreement with the radio continuum and the IR filaments. From these observations, it is clear that OH absorption also traces regions of interaction between SNRs and molecular clouds. OH absorption is not only a more generic tracer of SNR-molecular cloud interactions than OH masers at 1720 MHz, but also does not need a bright continuum background to be detectable (McDonnell 2010).

An interesting result is derived from the extended maser emission in IC443. Claussen et al. (1997) detected six compact masers clustered in a single spot projected onto this SNR. Hewitt, Yusef-Zadeh & Wardle (2009) uncovered several other clumps towards different directions in the SNR. For clump B, they could separate spectrally the pre- and post-shock gas. Under the assumption of local thermodynamical equilibrium, the 1667 MHz line can be used to compute the OH column density as

$$N_{OH} = 2.2785 \times 10^{14} T_{ex} \int \tau_v dv \text{ cm}^{-2}$$

(Crutcher et al. 1977). Replacing the spectral fits into this equation, the pre- and post-shock column densities are estimated to be  $9 \times 10^{13}$  and  $1.1 \times 10^{16} \text{ cm}^{-2}$  respectively, in very good agreement with theoretical predictions (see Section 3).

#### 4.2. Masers at other frequencies

So far, most maser surveys towards SNRs were focused on the ground state satellite line at 1720 MHz of the OH. Theoretical predictions (Wardle 2007, Pihlström et al. 2008) suggest that under the same physical conditions but with higher OH column densities, masers can be excited at higher energy levels. However, surveys conducted to detect OH masers at 6 GHz in 15 northern SNRs (Fish, Sjouwerman & Pihlström 2007) and in 35 southern SNRs (McDonnell, Wardle & Vaughan 2008) were unsuccessful. No detections were obtained either for four SNRs observed at 4.7, 7.8, 8.2, and 23.8 GHz (Pihlström et al. 2008). However, OH masers at 6 GHz are detected in several star-forming regions. It is possible that OH densities in SNRs never become so high as to excite masers at 6 GHz (McDonnell 2010).



Another molecule that, like the OH radical, can be collisionally pumped is methanol ( $\text{CH}_3\text{OH}$ ). The widespread distribution of  $\text{CH}_3\text{OH}$  makes its masers a potentially unique tool to detect molecular shocks. Zubrin & Shulga (2008) reported a first detection of a 95 GHz  $\text{CH}_3\text{OH}$  maser in Kes 79, which could not be confirmed by subsequent observations (Frail 2008). Methanol masers at 36 GHz (Sjouwerman, Pihlström & Fish 2010) and 44 GHz (Pihlström, Sjouwerman & Fish 2011) have been detected towards the interaction region between Sgr A East and a molecular ridge. The masers at 1720 MHz, 36 GHz and 44 GHz are not positionally coincident, meaning that the physical conditions under which each transition is amplified are not the same. Frail (2008) reported a preliminary VLA detection, in a partial data reduction, of a 44 GHz  $\text{CH}_3\text{OH}$  maser in W28. The confirmation is not published yet. Although 1720 MHz masers are not suitable for radio astrometry because they are extended, as revealed by VLBI observations (Brogan 2005), masers at higher frequencies associated with SNRs can potentially be used to measure distances and expansion velocities (e.g. Honma, Kawaguchi & Sasao 2000).

## 5. Magnetic fields

While local variations in the density distribution of the ISM have an impact on the evolution of SNRs, in many cases the peculiar morphology of a remnant cannot be ascribed to such inhomogeneities. As an example, let us consider two bilateral SNRs: G296.5+10.0 and SN 1006 (G327.6+14.6; fig. 2(a)). In radio continuum, both SNRs are characterized by two bright lobes with a high degree of symmetry with respect to an axis almost perpendicular to the Galactic Plane (Kesteven & Caswell 1987, Roger et al. 1988). Attempts have been made to explain this morphology through inhomogeneities in the ISM in the form of clouds, tunnels or elongated cavities, but HI surveys did not support this picture (Giacani et al. 2000, Dubner et al. 2002) since, as expected for SNRs far above the Galactic Plane like in these two cases, the ISM is highly homogeneous.

G296.5+10.0 is believed to come from a core collapse event, as evidenced by its central X-ray pulsar (Zavlin et al. 2000). Massive stars undergo mass losses during their lives through strong winds, creating bubbles in the ISM. If the stellar wind is magnetized, Chevalier & Luo (1994) propose that the toroidal magnetic field is amplified and thus the bubble will be elongated in the polar direction because the magnetic tension will constrain the flow in the equatorial direction.

Harvey-Smith et al. (2010) performed a polarimetry study of G296.5+10.0 focusing on the analysis of the Faraday rotation, and found that the rotation measure (RM) in the eastern and in the western lobes have opposite signs. This pattern implies that the magnetic field component parallel to the line of sight points towards or against us on either side of the symmetry axis. The reversal in the magnetic field orientation, as well as the magnitude of the RM, are well explained by an azimuthal magnetic field in the stellar wind of a red supergiant progenitor.

The case of SN 1006 is different. There is a general agreement in that this SNR is the result of a type Ia event. The shape of the shell is quite circular, in contrast to the elongated morphology of G296.5+10.0. Thus, the argument of a magnetized wind prior to the explosion does not hold here. Still, the pre-existent interstellar magnetic field seems to have played a key role in the bilateral morphology of this SNR, as discussed below.

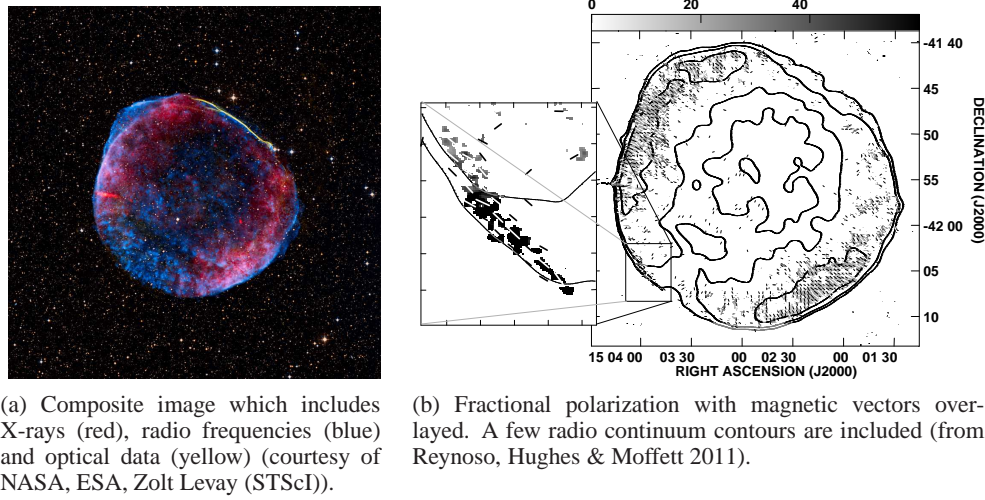


Figure 2. Images of SN 1006.

Fulbright & Reynolds (1990) simulated bipolar morphologies in SNRs under two assumptions, depending on whether particle injection and acceleration was more efficient in parallel shocks or in perpendicular shocks, where parallel and perpendicular refer to the relative direction between the magnetic field and the normal to the shock front. In their model, the two limbs correspond to polar caps in the first case and to an equatorial belt in the second. Rothenflug et al. (2004) analyzes an XMM-Newton image of SN 1006 and concludes that the geometry is explained considering the lobes as two polar caps. The picture, however, is not clear since radio observations prefer the equatorial belt geometry (Schneider et al. 2010 and references therein).

Reynoso, Hughes & Moffett (2011) carried out a polarization study of SN 1006 and found that while the magnetic field orientation is predominantly radial at the bright lobes, it is tangential at the SE, where the radio emission is extremely weak (fig. 2(b)). At the same time, the fractional polarization is about 17% in the lobes but raises up to almost the theoretical value of 71% at the SE (see inset in fig. 2(b)). The distribution of the orientation of the magnetic field vectors in the lobes can be fitted by a broad component extending from  $0^\circ$  to  $90^\circ$ , and a narrow peak centered at  $60^\circ$ , which is coincident with the direction of the Galactic Plane (Reynoso, Hughes & Moffett, in preparation).

If the direction of the interstellar magnetic field towards SN 1006 is parallel to the Galactic Plane, then we can conclude that particle injection and acceleration are more efficient in parallel shocks. The low polarization fraction at the lobes agrees with a turbulent magnetic field. Those spots where the magnetic field is locally amplified act as centers of diffusion for particle acceleration in collisionless shocks. On the contrary, in regions where the magnetic field is highly ordered and then particle acceleration is inefficient, we expect both very weak synchrotron emission and a high degree of polarization, as observed at the SE. This scenario is further supported by the recent detection of VHE emission from the lobes with H.E.S.S. (Acero et al. 2010).

## 6. Conclusions

Since in most cases VHE emission from SNRs can be explained by a hadronic origin, the detection of such emission is evidence not only of interaction between SNRs and molecular clouds, but also of CR acceleration in SNRs. On the other hand, extended maser emission at 1720 MHz appears to be a common phenomenon and may be the reason for the paucity of compact OH masers detected so far. Moreover, extended emission, as well as absorption in the main lines (1665 and 1667 MHz), are good tracers of wider extensions of shock front interactions with molecular gas. OH masers at higher frequencies are theoretically predicted but remain still undetected, while there are claims of detection of methanol masers which need confirmation. Masers at frequencies higher than 1720 MHz can be useful to measure distances and expansion velocities of close SNRs through radio astrometry. Finally, the CSM or ISM can determine the morphology of a SNR through their magnetic fields even if the gas density distribution were homogeneous.

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